EFFECTS OF FILTRATION ON THE IMPULSE BREAKDOWN STRENGTH OF HIGH-PURITY WATER

Dr. Victor H. Gehman, Jr., Dr. Ronald J. Gripshover, and Dr. Thomas L. Berger
Pulsed Power Systems and Technology Group, Code B20
Dahlgren Division, Naval Surface Warfare Center
17320 Dahlgren Road
Dahlgren, Virginia 22448-5100
and
Dr. Samuel P. Bowen
Division of Educational Programs, Argonne National Laboratory
9700 South Cass Avenue, DEP/223
Argonne, Illinois 60439-4845
and
Dr. Royce K. P. Zia
Physics Department, Virginia Tech
Blacksburg, Virginia 24061

Abstract

High-purity water is the dielectric of choice for most pulsed-power machines. Increasing the electrical breakdown strength of high-purity water is one of the principle goals for pulsed power, because the energy density stored in the water increases as the square of the electric field.

This paper concentrates on the impulse breakdown strength for long-stress times (i.e., greater than 65 microseconds). Previous work at Dahlgren has shown that the breakdown strength is independent of stress time in this regime.

Our hypothesis is that impurities control the breakdown behavior of nominally high-purity water. Specifically, we will present experimental data that shows the use of filtration methods designed to remove organic material and particulates (which don't affect the resistivity of water), improves the breakdown strength. Earlier results that showed a time variation for improvements in breakdown strength will be explained. An experimental design to achieve even greater improvements in breakdown strength will be presented.

Introduction

For several years we've been pursuing a hypothesis that asserts that the initiator for electrical breakdown for long charging time (i.e., greater than 65 μs) in "high-purity water" is an non-ionic impurity particle or aggregation. Evidence for this hypothesis is circumstantial but statistically significant and compelling. Changes to the water-purification cycle, to decrease non ionic contaminants in the water dielectric, increase the electrical breakdown strength.

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14. ABSTRACT
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Experimental Set-up

The basic electrical and water-purification apparatus has been described in previous papers[1 2]. Improvements to reduce non-ionic contaminants occurred in two phases. The first phase involved the introduction of industrial-grade plastic particulate filters followed by an organic-filter cartridge[3]. A by-pass was provided around the organic filter to examine the effects of particulate filtering only. Please see Figure 1. Also included in the first phase was the removal of all Tygon tubing from the piping system because of its tendency to leach plasticizer into water. However, no effort was made to introduce a roughing cartridge for the organic filter, which had results that will be discussed later.

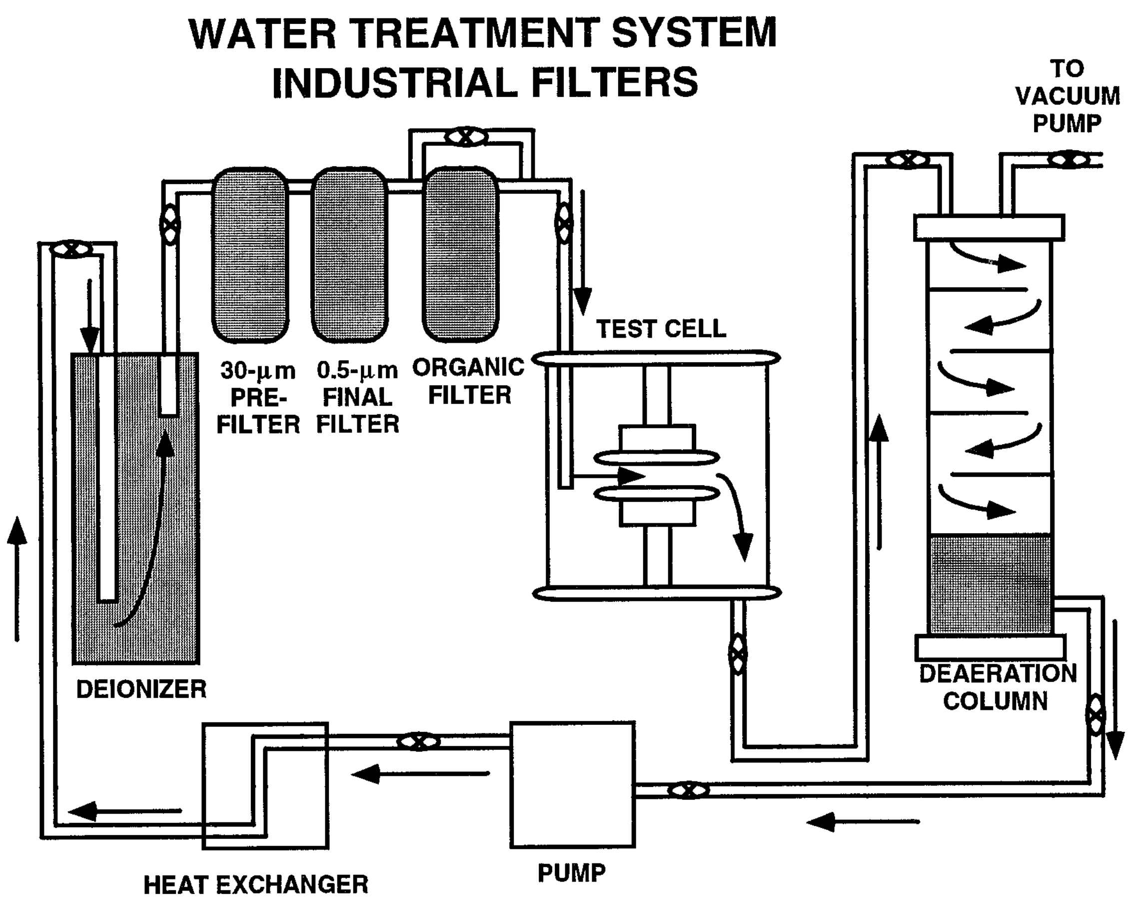

Figure 1. The sketch of the first-phase upgrade, using industrial-grade filters, to the water-treatment apparatus for the electrical-impulse, water-breakdown experiment.

Subsequently, as a result of experiments described below, we designed and built a second-phase apparatus. This incorporated a roughing filter for both deionization and non-ionic filtration, a deionization cartridge, an organic-contaminant-removal cartridge and a final particulate filter. Please see Figure 2. These components were higher-quality laboratory-grade units. To ensure adequate flow, four parallel banks were used.

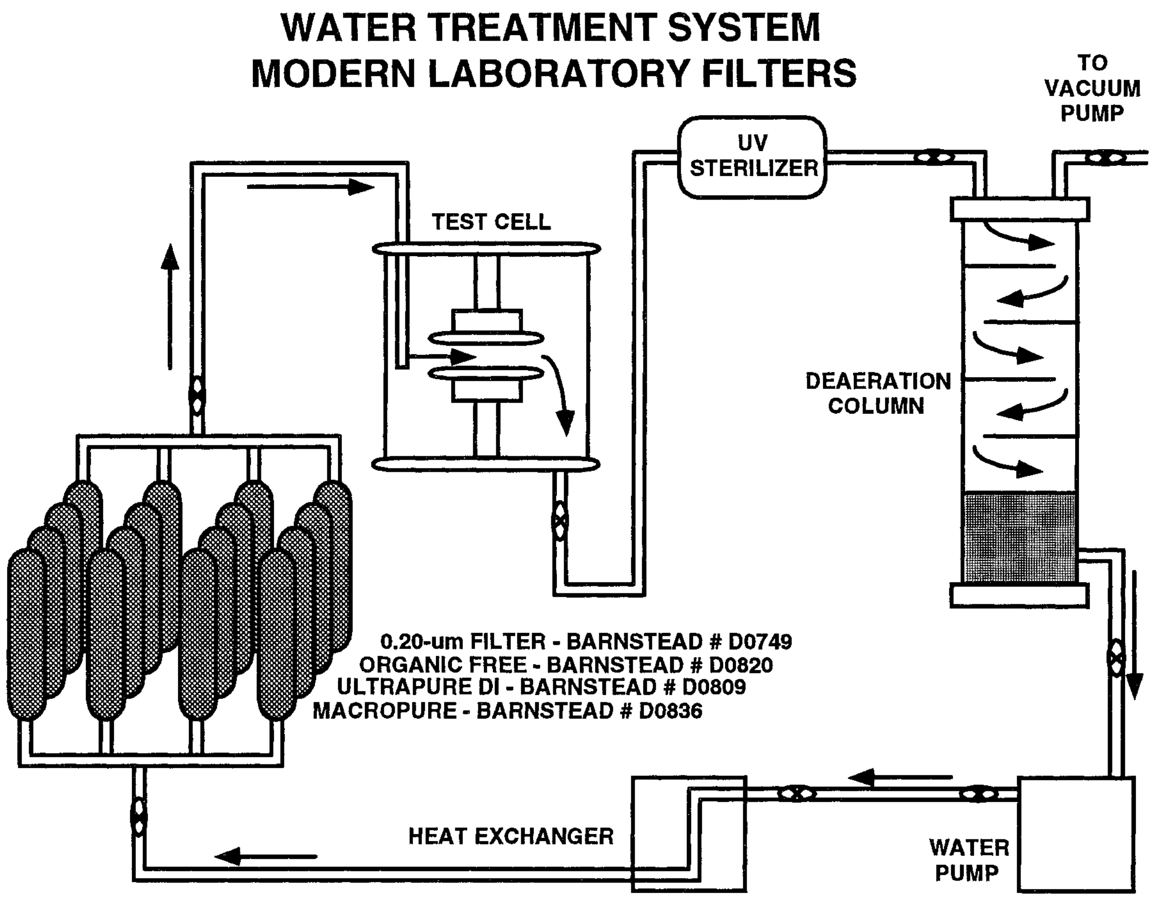

Figure 2. The sketch of the second-phase upgrade to the water-treatment apparatus for the electrical-impulse, water-breakdown experiment.

Experimental Results

In a previous paper, we discussed the beneficial results of adding the first-phase upgrade of the water-conditioning apparatus to experiments on the electrical breakdown strength of copper electrodes. Figure 3 is a representation of three days of data with the mean and standard deviation plotted for different conditions. Clearly, the addition of particulate filters improved the breakdown strength and reduced the scatter. The addition of organic filters also improves the breakdown strength and keeps the scatter low.

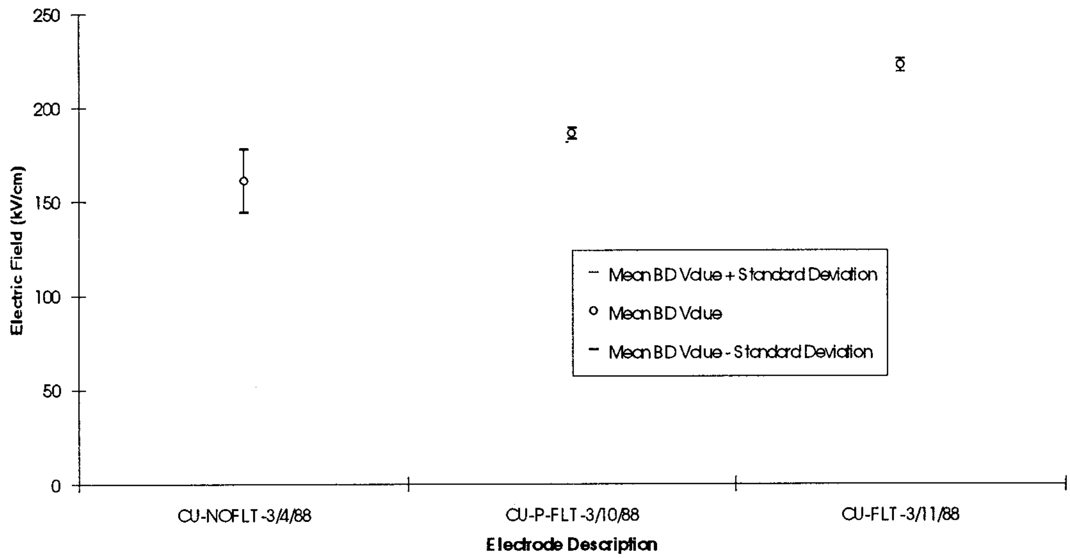

Figure 3. Plot of the mean breakdown field plus or minus the standard deviation for a series of experiments on copper demonstrating the efficacy of first-phase-upgrade filter combinations. On the left is no filters, in the center is only particulate filters, and on the right is the combination of particulate plus organic filter.

Unfortunately, over time the breakdown strength for this experimental configuration was unstable, as seen in Figure 4 for copper electrodes and in Figure 5 for tungsten electrodes. After careful review, we hypothesized that there were several flaws with our first-phase upgrade to the water-conditioning system. Namely, there was no roughing filter for the organic-free cartridge, the quality control for the particulate filters was not high, and finally the size of the final filter was too large to guarantee trapping all bacteria. The absence of a roughing filter for the organic-free cartridge was probably the biggest mistake, because these cartridges are known to become exhausted quickly if pre-filtering is not provided.

Therefore, we designed the following improvements for the second-phase upgrade to the water-conditioning system. Firstly, there is now a macrorecticular cartridge that serves as a prefilter to both the deionization and organic-free cartridges. Secondly, all the filters are now laboratory grade with a high degree of quality control during manufacture. And finally, the final particulate filter is rated at 0.2 μm. There are more improvements that could have been made, but funding restraint forced us to limit ourselves to these changes. There will be more discussion of this subject later.

Results of testing the second-phase upgrade on tungsten electrodes is presented in Figure 6 as a comparison to the results in Figure 5. The mean breakdown strength increased while the scatter decreased. Funding restraints limited the amount of testing possible over the succeeding years, but a summary of the tests results for various electrode materials is presented in Table I for water using the old conditioning system and in Table II for water treated with either the first-phase or second-phase upgrade to the water-conditioning system. Clearly, the upgraded systems gave improved breakdown performance. Tungsten was the only material which had a statistically significant number of tests for both water-upgrade systems. As can be seen in Table II, the second-phase upgrade is better.

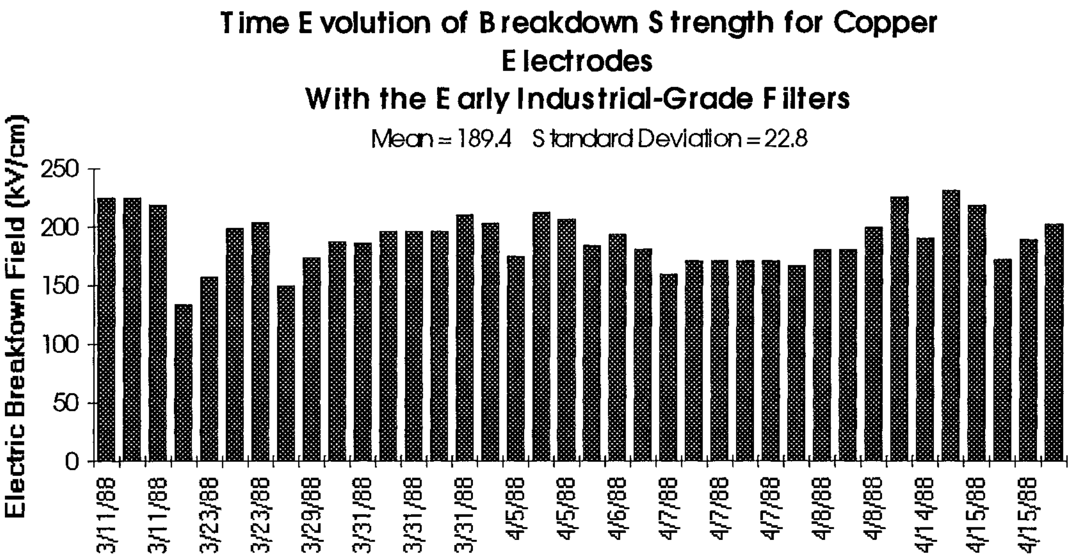

Figure 4. Breakdown data for copper electrodes with the first-phase-upgrade particulate filters and a Barnstead organic filter. Note the erratic behavior after the initial runs on 3/11/88.

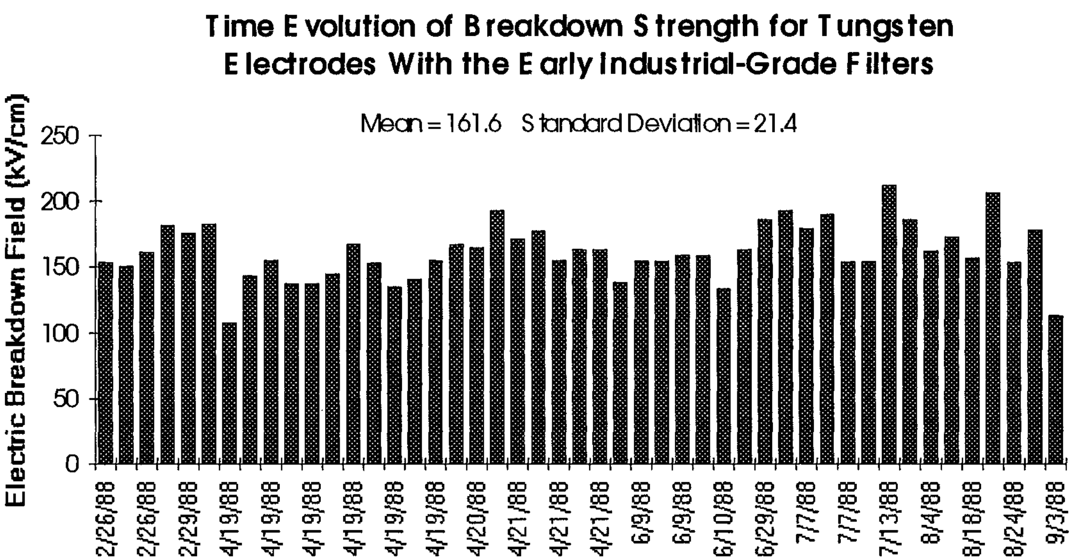

Figure 5. Breakdown data for tungsten electrodes with first-phase-upgrade particulate filters and a Barnstead organic filter. Note the erratic behavior.

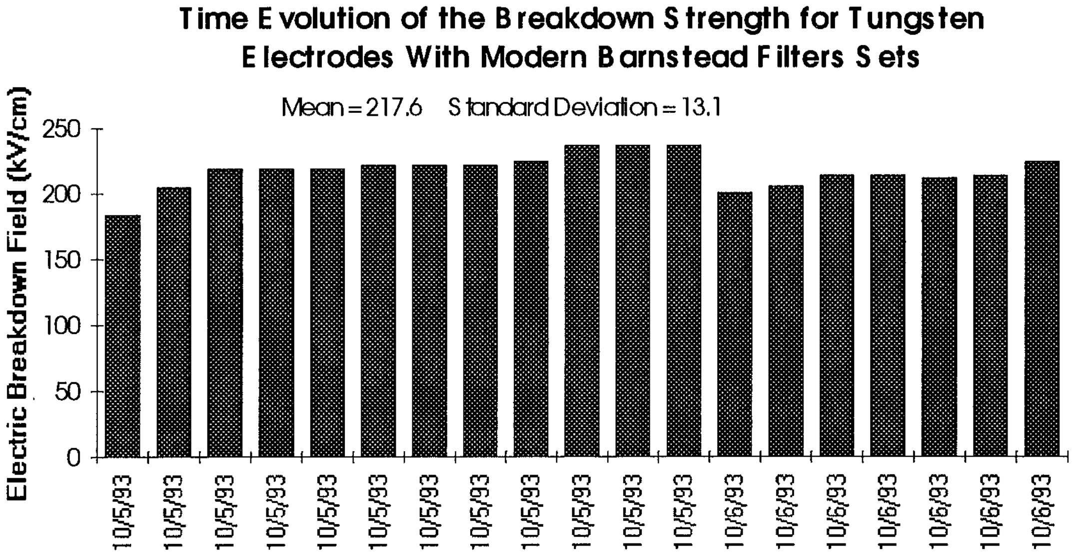

Figure 6. Breakdown data for tungsten electrodes with second-phase-upgrade Barnstead particulate and organic filters. Note the more consistent breakdown behavior as compared to Figure 5. Also note that the mean breakdown strength is increased.

Table I. Electric-field breakdown results by material for the old conditioning system.

Material	Breakdown (kV/cm)	Standard Deviation
Graphite	137	25
Stainless Steel	145	16
Aluminum	159	8
Copper	161	16
Gold	168	13
Lead	169	8

Table II. Comparison of electric-field breakdown results for the old conditioning system versus the upgraded-conditioning system for water.

Material	Breakdown (the average breakdown field and the standard error of the mean) without Filters (kV/cm)	Breakdown (the average breakdown field and the standard error of the mean) with Filters (kV/cm)
304SS	128 ± 5	174 ± 8 (Particulate only)
304SS	128 ± 5	190 ± 3 (Both)
Copper	161 ± 8	186 ± 2 (Particulate only)
Copper	161 ± 8	222 ± 2 (Both)
Tungsten	N.A.	163 ± 3 (Both) 161.6 (First Phase Upgrade) 217.6 (Second Phase Upgrade)

In Table II, (Both) refers to using activated charcoal as well as the particulate filters. We assume that activated charcoal binds organic fragments smaller than 0.5 (and later 0.2) microns as well as organic molecules themselves. Efficiency of the filters and the concentration of non-ionic contaminants were not monitored. Yet, the large increase of the breakdown field with the inclusion of the organic filters is striking evidence of the effect of organic-based impurities in the system. The water quality for these samples was kept as high as possible and these data were taken after the Tygon hoses were taken out of the system. Thus, these data should be the closest to representing the measurement of the pure-electrode-breakdown effect. Tungsten was measured with the complete set of filters, though there was no statistically significant data, with no filters, for comparison.

<u>Discussion of Other Factors That Affect Breakdown Behavior</u>

- Bubbles and deaeration of the liquid dielectric

Bubbles are a clear and well known source of breakdowns. If there are observable bubbles on the surface of the plates of the capacitor, the breakdown is overwhelmingly likely to initiate at the bubble. In order to suppress the formation of bubbles, the water was deaerated and kept at low temperatures. Under these conditions bubbles would not form spontaneously or, if formed, would collapse fairly quickly. For the bulk of the data reported here there were no observable bubbles.

- Temperature

The temperature of the water was kept very low (i.e., about 10 C) and constant in almost all of the experiments. On those occasions where the temperature was not controlled, spurious breakdowns were observed to occur. These were often associated with temperature changes and thus expansion or contraction of the system which would flush material out into the circulating water. For the most part, temperature was well controlled to keep the intrinsic time constant of the system in the range of 300 microseconds.

Conclusions

Careful conditioning of high-purity water is critical to obtaining high electric-breakdown strength. A steadily improving progression of techniques has been developed to condition water, and the results have been measured and analyzed with statistics. Whenever measures have been adopted to reduce the concentration of ionic and non-ionic impurities in the water, the mean breakdown strength has improved.

Furthermore, the equipment to monitor in real time the concentration of non-ionic impurities is not incorporated into the system. Therefore, no quantitative relationship can be deduced.

It is unknown whether the electrical-breakdown strength of water will continue to improve if more measures to reduce non-ionic contamination are adopted However, there is nothing to suggest that the ultimate breakdown strength of water has been reached. In our opinion continued research in this area is justified.

Suggestions For Future Experiments

Clearly, the next experimental step would involve construction of a new breakdown apparatus using only the best materials for high-purity water systems; namely, polyvinylidene fluoride (PVDF) or polypropylene (PPP) for non-metallic components. Any metallic components needed in the system would be matched to the electrodes under test. Also, an in-line real-time monitor for non-ionic contaminants is now available from several companies. Incorporation of this device could lead to a quantitative relationship between breakdown and impurity level. Perhaps this set-up could finally observe the breakdown of pure water for a given electrode material. Then we could proceed with the investigation into the effects of electrode surface on breakdown. This system could be built for tens of thousands of dollars and is quite feasible within the scope of today's technology.

Finally, to directly ascertain the cause for the breakdown initiation, we would need an in-situ instrument, capable of microscopic examination (nanometer by nanometer) of the electrode surface under high-electric-field conditions with a time resolution of a few tens of picoseconds. Then we could observe the proto-streamers and determine the conditions under which they grow into breakdowns. Unfortunately, this device is impractical at this time and we will have to content ourselves with indirect evidence as to the nature of high-purity-water electrical breakdown for the indefinite future.

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[1]D. B. Fenneman and R. J. Gripshover, "Experiments on Electrical Breakdown in Water in the Microsecond Regime", *IEEE Trans. Plasma Sci.*, Vol. PS-8, No. 3, pp. 209-213, Sept. 1980.

[2]D. B. Fenneman and R. J. Gripshover, "Experiments on Electrical Breakdown in Water in the Microsecond Regime", *Proc. 2nd IEEE Int. Pulsed Power Conf.*, pp. 122-126, June 12-14, 1979.

[3]V. H. Gehman, Jr., L. B. Atwell, D. A. Dorer, and R. J. Gripshover, "Determination of Electrical Breakdown Strength for Various Materials in Pure Water", IEEE 1988 Eighteenth Power Modulator Symposium, pp. 385-388, 20-22 June 1988.